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Relationship of Optical Coating on Thermal Radiation Characteristics of Nonisothermal Cylindrical Enclosures

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RELATIONSHIP OF OPTICAL COATING ON THERMAL RADIATION CHARACTERISTICS OF NONISOTHERMAL CYLINDRICAL ENCLOSURES

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SUMMARY

The ability of a cavity to radiate energy (performance) is based on its capacity to absorb and emit radiation from its various internal surfaces. A numerical ray tracing technique was applied to simulate radiation propagating from various nonisothermal cylindrical cavities to determine the effect of optical coatings (surface emissivity). The statistical numerical ray tracing computer code NEVADA was used to determine the energy relationships between the cavity dimensions, surface emissivity values, and temperature profiles. By comparing the cavity performance (apparent emissivity), patterns became apparent between optical coatings and surface temperatures as a function of cavity dimension. In general, for nonisothermal cavities the optical coating and temperature within the cavity has a significant effect on its radiation performance. Temperature thresholds were found to exist where the same optical coating may result in either minimizing or maximizing its effect on cavity performance. Parametric values of apparent emissivity results are presented over a wide range of variables to correlate cylindrical cavity radiation for nonuniform cavity emissivity values. A universal curve has been developed to aid in selecting wall emissivity values for design considerations.

INTRODUCTION

The thermal radiation characteristics of partially enclosed surfaces (cavities or enclosures) are of great interest and have resulted in considerable amounts of work in this area. The principles of radiation exchange for cavity surfaces lead to complex enclosure theories due to nonuniformly distributed radiant energy. Each surface within a cavity may emit multi-reflecting radiation that can be partially or totally absorbed within the cavity or emitted to its surroundings. Depending on the cavity optical coating (surface emissivity value) and geometry, the energy leaving the cavity surfaces may be composed of direct emission plus possible reflected energy.

Various theoretical techniques have been applied to analyze isothermal and nonisothermal cavities. The verification of the numerical ray tracing technique for use in studying cavity radiation propagation is referenced in Baumeister (1990), where isothermal and nonisothermal gray-diffuse cylindrical geometries with uniform surface emissivity values were evaluated and compared with known solutions. The numerical ray tracing code that simulates the electromagnetic theory of radiation in this reference will again be used for analyzing the nonuniform surface emissivity values within nonisothermal cavities.

A schematic diagram of the cylindrical cavity analyzed in this study is shown in figure 1. The cylinder and disk wall sections of this cavity are at different temperatures and surface emissivity values. This cylindrical gray-diffuse cavity analysis varies the cavity length L, radius R, surface emissivity value combinations, and temperature distributions within the cavity. The goal of the parametric study is to provide insight into cylindrical cavity radiation propagation from various surface emissivity value combinations for possible use as a design reference.

SYMBOLS

A	surface area
B	radiation interchange factor
E	energy emitted per unit time
L	cavity length
n	n^{th} surface
R	cavity radius
T	absolute temperature
ε	emissivity
ε_a	apparent emissivity
σ	Stefan-Boltzmann constant

Subscripts:

C	cylinder surfaces
D	disk surfaces
i,j	i^{th} and j^{th} surfaces
out	cylinder exit area
∞	space (projected out of cavity), infinity

METHOD OF ANALYSIS

There are several varieties of thermal analysis codes available to model energy flux distributions for various geometries. Each code may have different solution techniques and advantages. The Net Energy Verification And Determination Analyzer program (1988), referred to as NEVADA, was selected to simulate the radiation propagation within and from a cylindrical cavity. NEVADA is a software package consisting of several programs in which a Monte-Carlo mathematical technique is applied to radiation propagation. The NEVADA program was attractive to use because of its ability to handle specular radiation and, most importantly, complex geometries.

In the NEVADA code, a statistical numerical method using the Monte-Carlo technique is applied to a ray tracing procedure to model radiation exchange. The ray tracing procedure mathematically traces emitted rays (simulating emitted radiation) as they propagate throughout the cavity. Each ray leaving a surface is considered a bundle of photons. Each photon bundle carries equal, discrete, amounts of energy. The path of the bundles (rays) may interact with various surfaces, all of which may reduce the energy of the bundle. The interacting surfaces may have different thermal properties and geometric configurations that may affect each bundle's propagation differently. By accounting for all the emitted bundles as they propagate throughout the cavity, percentages of incident and absorbed energy at desired locations can be computed. The percentages of absorbed energies are then applied to the energy balance equations.

ANALYSIS

In studying cylindrical cavity configurations, the overall performance of a cavity is defined as an apparent emissivity (ε_a). The apparent emissivity is the actual amount of energy leaving the cavity compared with that of blackbody emission, or:

$$\varepsilon_a = \frac{E_{out}}{E_{blackbody}} \tag{1}$$

This apparent emissivity relates direct emitted and reflected radiation leaving the cavity to blackbody radiation. Due to the nonuniform distribution of radiation within the cavity (radiosity and irradiation), calculating the energy emitted from the cavity becomes complicated. Approximate analytical solution for the radiation exchange integral equations were first derived by Buckley (1927,1928) and Eckert (1935), and later improved to greater numerical accuracy by Sparrow and Albers (1960).

The numerical ray tracing technique enables one to evaluate the radiation heat transfer from a multisectioned cavity to its various sections and the radiation projected out the cavity. The numerical ray tracing technique actually maps radiation as it propagates from surface to surface according to the governing heat transfer equation:

$$E_{out} = E_{i-j} = \varepsilon \sigma A_i B_{i \to j} \left(T_i^4 - T_j^4 \right) \tag{2}$$

The i and j represent various sections of cavity surfaces such as a disk wall D, cylinder wall C, or its opening (space). The blackbody view factor is replaced by the radiation interchange factor B that represents real surface radiation exchange. The radiation interchange factor is a function of the blackbody view factor and the emissivity from all energy exchanging surfaces. The radiation interchange factor is the fraction of energy emitted by a real surface i that is absorbed by a real surface j, including all reflections from other real surfaces including the emitting surface i. For this cavity analysis the surfaces are emitting and reflecting diffuse radiation. The apparent emissivity for a multisection cavity where n represents the number of each individual section becomes:

$$\varepsilon_a = \frac{\sum_{i=1}^{n} \varepsilon_i \sigma A_i B_{i \to \infty} \left(T_i^4 - T_\infty^4\right)}{\sigma A_{out} \left(T_D^4 - T_\infty^4\right)} \tag{3}$$

where the blackbody radiant energy, represented in the denominator, is defined by the area projected out the cavity at the disk temperature. The focus in equation (3) is determining the amount of energy leaving each surface i $(T_D \geq T_i)$ and reaching the cavity opening ∞.

Using the numerical ray tracing approach, a cavity can be divided into any number of desired sections, within computer computational limits. This analysis divides the cavity into two sections. The disk wall D and cylinder wall C comprise the cavity model shown in figure 1. For the geometry in figure 1, equation (3) reduces to:

$$\varepsilon_a = \frac{\varepsilon_D \sigma A_D B_{D \to \infty} \left(T_D^4 - T_\infty^4\right) + \varepsilon_C \sigma A_C B_{C \to \infty} \left(T_C^4 - T_\infty^4\right)}{\sigma A_{out} \left(T_D^4 - T_\infty^4\right)} \tag{4}$$

Because the actual energy of the rays is determined after multiple surface reflections, there are no requirements for uniform surface radiosity and therefore no surface sectioning would be required. This makes dividing the disk and cylinder into smaller sections unnecessary, as would be required with a radiation resistor network analysis solution. As long as a surface has a uniform temperature profile and surface emissivity value, one is only limited by defining the cavity's internal surface geometry. The validation with limiting solutions for the numerical ray tracing technique are referenced in Baumeister (1990), and summarized in appendix A. The variables in equation (4), (i.e., surface areas, temperatures, surface emissivity values, and radiation interchange factors) can be interrelated in calculating the cavity apparent emissivity. By performing parametric studies over these variable ranges, cavity radiation performance can be characterized.

DISCUSSION OF RESULTS

A cavity's ability to emit radiant energy is a function of the cavity wall temperatures, dimensions and surface emissivity values which may be nonuniform. Analyzed cases consisted of cavity dimensions (L/R) ranging from an extremely small cavity L/R = 0.5 to a large cavity L/R = 8.0, while evaluating combinations of surface emissivity values (ε) of 0.2, 0.5, and 0.8 within the cavity. Each analyzed case will display the cavity's ability to radiate energy as an apparent emissivity and an apparent emissivity ratio. The apparent emissivity ratio compares the nonuniform emissivity (ε_D not equal to ε_C) case to a uniform emissivity case (ε_D equal to ε_C) as an alternative means for comparison.

Figures 2 to 6 display the effect of uniform and nonuniform surface emissivity values on cavity apparent emissivity results based on equation (4), for various cavity length-to-radius ratios (L/R). Results from the various cavity configurations display the cavity apparent emissivity (ε_a) as a function of the wall temperature ratio. By using ε_a from these curves, one could use equation (1) to calculate the energy emitted out the cavity. The wall temperature ratio displayed on the x-axis relates the cylinder temperature to the disk temperatures. This temperature ratio is represented by the following equation, where the environmental temperature is assumed at absolute zero:

$$\text{Temperature Ratio} = \frac{T_C - T_\infty}{T_D - T_\infty} = \frac{T_C}{T_D} \tag{5}$$

For low temperature ratios and large values of L/R, as seen in figures 5 and 6, it is difficult to interpret the change in magnitude of the apparent emissivity results as T_C/T_D approaches zero. To aid in interpreting the magnitude differences, the apparent emissivity ratio plots are used. The apparent emissivity ratio plots display magnitude differences between non-uniform surface emissivity cases and uniform surface emissivity cases. These curves reveal the normalized magnitude of possible gains or losses between the selection of surface emissivity values.

Apparent emissivity results for any particular cavity dimension (L/R), show that a relationship exists between the surface emissivity values and temperature ratio. The plots reveal that upon reaching a specific cylinder wall temperature, changes in surface emissivity have a reverse effect on cavity performance. Therefore, the cylinder wall emissivity value may result in either minimizing or maximizing the cavity performance, depending on the cylinder wall temperature. The location where the apparent emissivity curves converge for the various surface emissivity values will be referred to as the cylinder emissivity threshold point. For practical purposes (except for large L/R) the intersections of the converging curves are treated as a single point.

For low cylinder to disk temperature ratios, the cylinder walls are not a major source of emitted energy. At these low temperature ratios the cylinder wall behaves primarily as a passive absorber. A cavity with low cylinder wall temperatures emits less energy while absorbing multi-reflecting radiant energy along the disk and, more importantly, the cylinder wall. Thus, below the threshold point, increasing the cylinder wall emissivity value reduces the energy emitted from the duct by increasing the absorption along the cylinder wall. In contrast, for high cylinder to disk temperature ratios, the cylinder wall is the major source of emitted energy due to their increased level of direct emitted radiation out the cavity. Thus, above the threshold point, increasing the cylinder wall emissivity value increases the energy emitted from the duct.

Inspection of the various apparent emissivity plots in figures 2 to 6 reveals that the cylinder emissivity threshold points shift also as a function of cavity dimensions, cylinder wall temperatures, and disk and cylinder emissivity values. For any fixed cylinder wall emissivity value, increasing the cylinder wall surface temperature beyond the threshold point results in the cylinder wall becoming the dominant factor for cavity emitting energy, as seen by moving to the right in the apparent emissivity plots in figure 2 to 6. However, because of the nearly flat apparent emissivity profiles below the emissivity threshold points in the figures, surface emissivity values and L/R ratios become the dominant factors associated with the emitted energy at or below the threshold point. The existence of a relationship between cavity dimensions and surface emissivity values as a function of cylinder wall temperatures is a significant factor associated with emitted energy. Therefore, to obtain a desired cavity radiant energy performance level, one may be required to evaluate the relationships between cylinder wall temperatures, surface emissivity values and dimensions. Through the process of analyzing these cavity variables and plotting their effect on cavity performance, the temperatures at which the cylinder wall dominates over other cavity variables such as dimensions and surface properties is now defined.

By incorporating the cylinder emissivity threshold points into one plot, figure 7 shows the cylinder and disk radiant energy dominating regions are a function of cavity size, surface temperatures and surface emissivity values. The curves separating the two regions represent the disk emissivity value within the cavity, and are used to defined the actual division from the two regions. For a fixed value of L/R in the lower disk dominant region, the cylinder emissivity value could be increased to absorb more energy from the disk, thereby decreasing the energy emitted from the duct. On the other hand, in the upper cylinder dominant region, the cylinder emissivity value could be decreased to emit less energy from the cylinder, thereby decreasing the energy emitted from the duct. In this cylinder dominant region, the cylinder wall temperature is the dominating source of thermal radiation emitted from the duct; this is clearly evident by referring back to the right side of the apparent emissivity plots in figures 2 to 6. Therefore, once in a particular surface dominating region, the energy emitted from the cavity can be increased or decreased depending on how the cylinder emissivity value is adjusted. Figure 8 illustrates an example on how to reduce cavity emission by adjusting the cylinder emissivity values for a particular cavity dimension and cylinder wall temperature. For a fixed L/R of 4, at a cylinder-to-disk temperature ratio of 0.4, an increase in cylinder emissivity would decrease emitted cavity energy; at a cylinder to disk temperature ratio of 0.8, a reduction in cylinder emissivity would decrease emitted cavity energy.

CONCLUDING REMARKS

For nonisothermal cylindrical cavities, a relationship exists between a cavity's ability to emit radiant energy and the cavity dimensions, surface emissivity values, and cylinder wall temperatures. Based on the ratio of cylinder-to-disk wall temperatures, a threshold exists where changing the cylinder wall emissivity value may result in either minimizing or maximizing cavity performance. The selection of surface properties (emissivity values) to either maximize or minimize the radiant energy from a cylindrical cavity requires careful examination of the cavity dimensions, surface wall temperatures, and the relationship between cavity component emissivity values.

By investigating various cylindrical cavity designs, one can grasp the effect of cavity parameters (i.e., dimensions, surface properties, and wall temperature profiles) on the emitted cavity radiation from possible cavity configurations. By performing these parametric studies over a wide range of cavity configurations, the nature of cavity radiation performance was characterized and may provide insight for use as a design reference.

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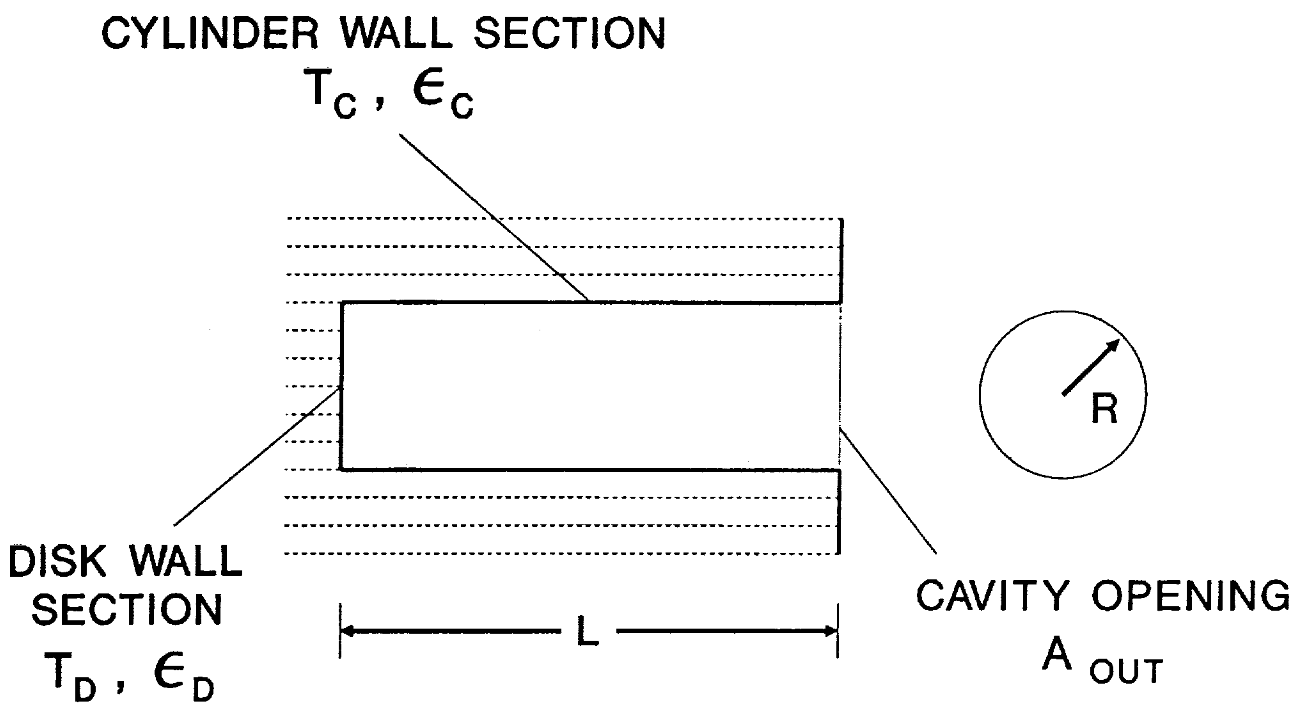

Figure 1.—Circular cylindrical cavity, cross section.

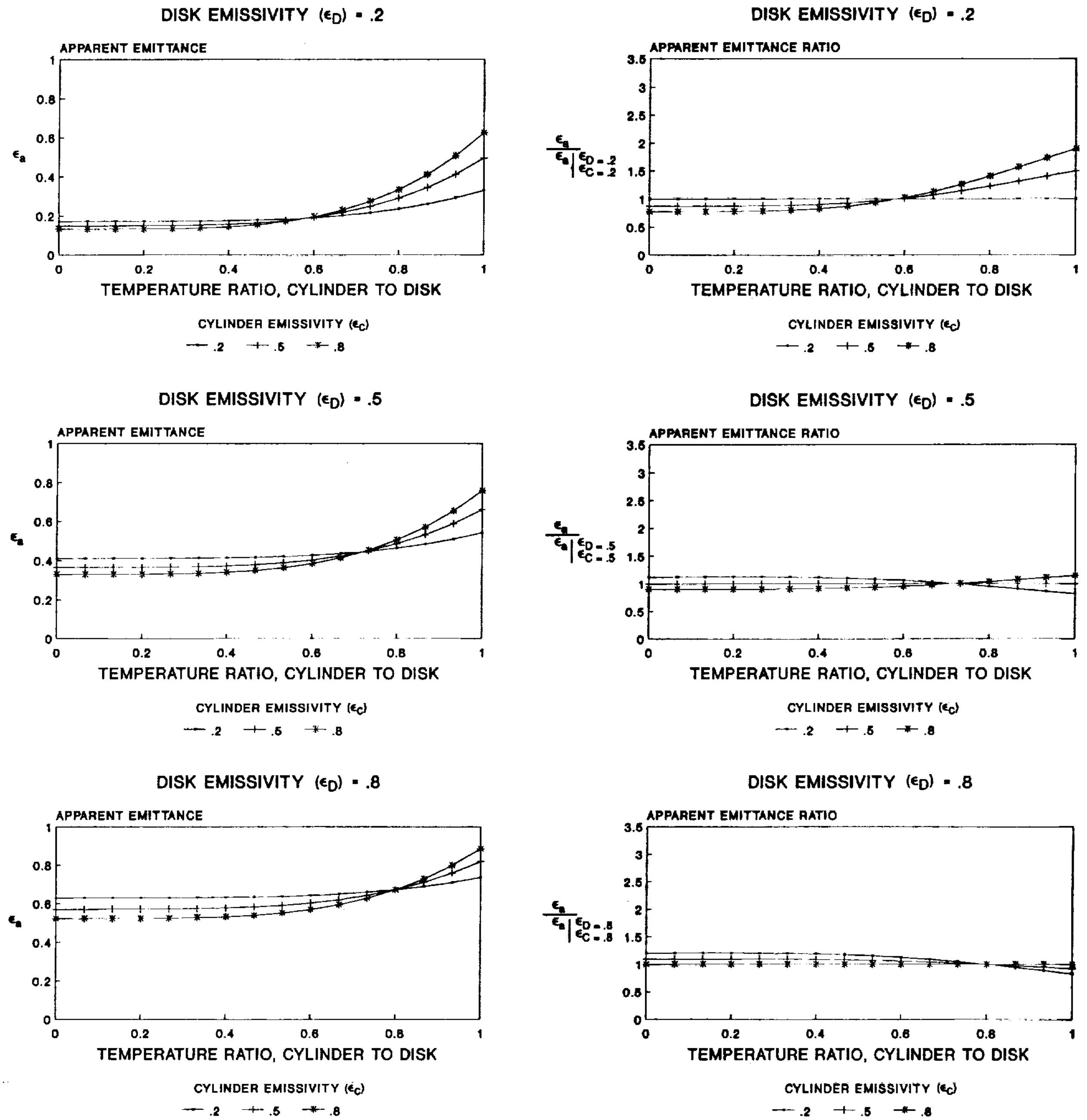

Figure 2.—Apparent emissivity results, L/R = 0.5.

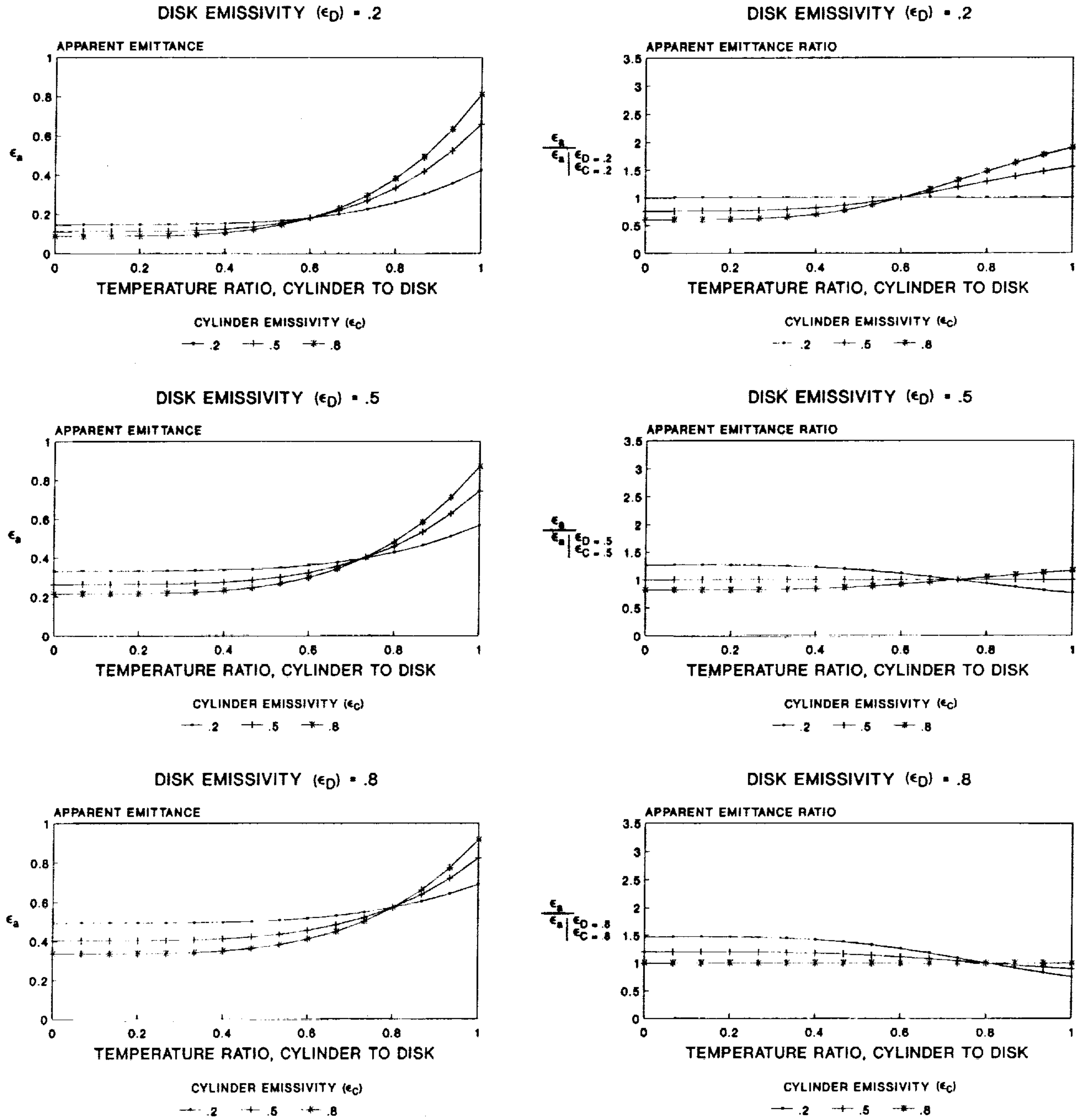

Figure 3.—Apparent emissivity results, L/R = 1.0.

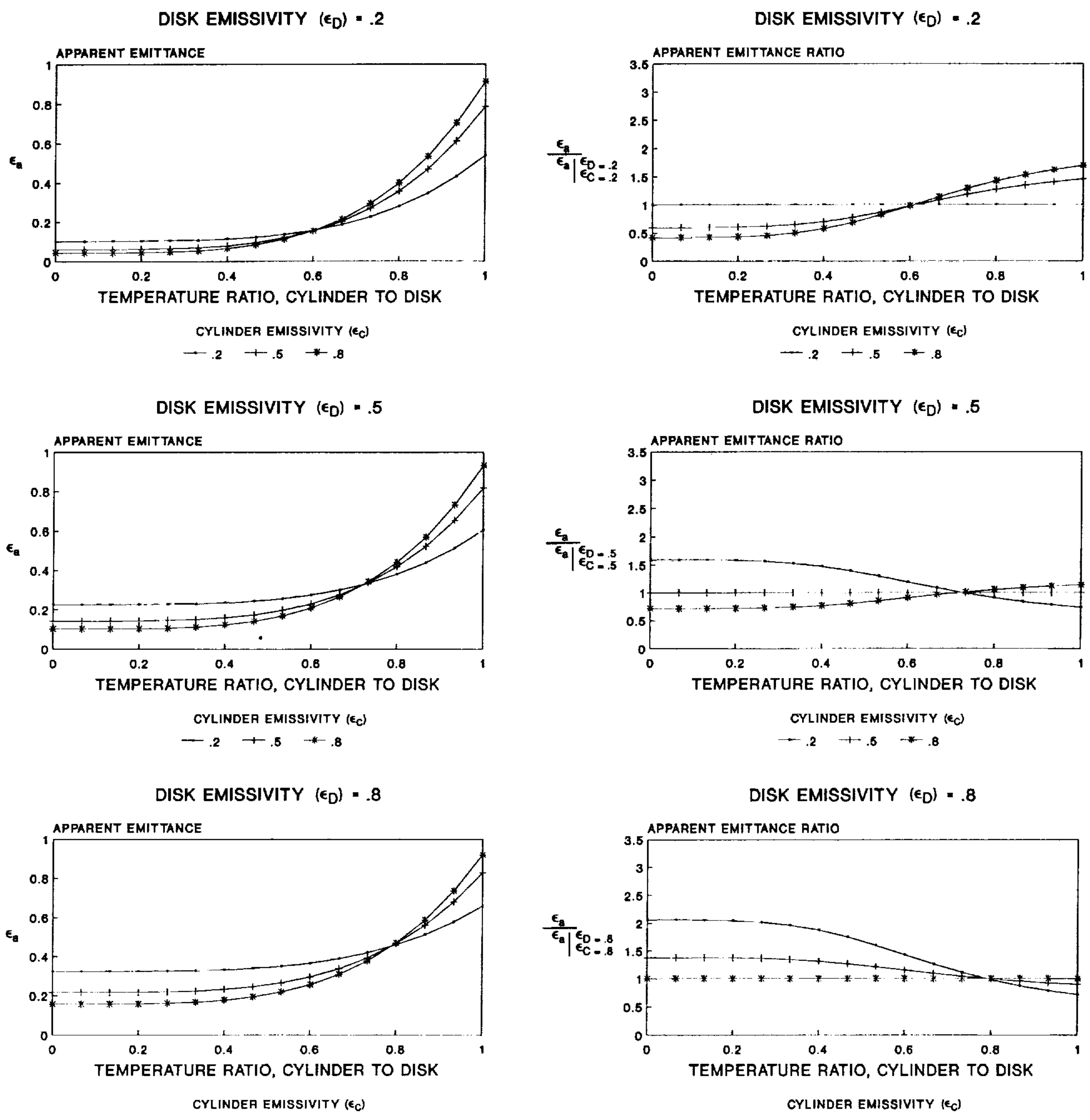

Figure 4.—Apparent emissivity results, L/R = 2.0.

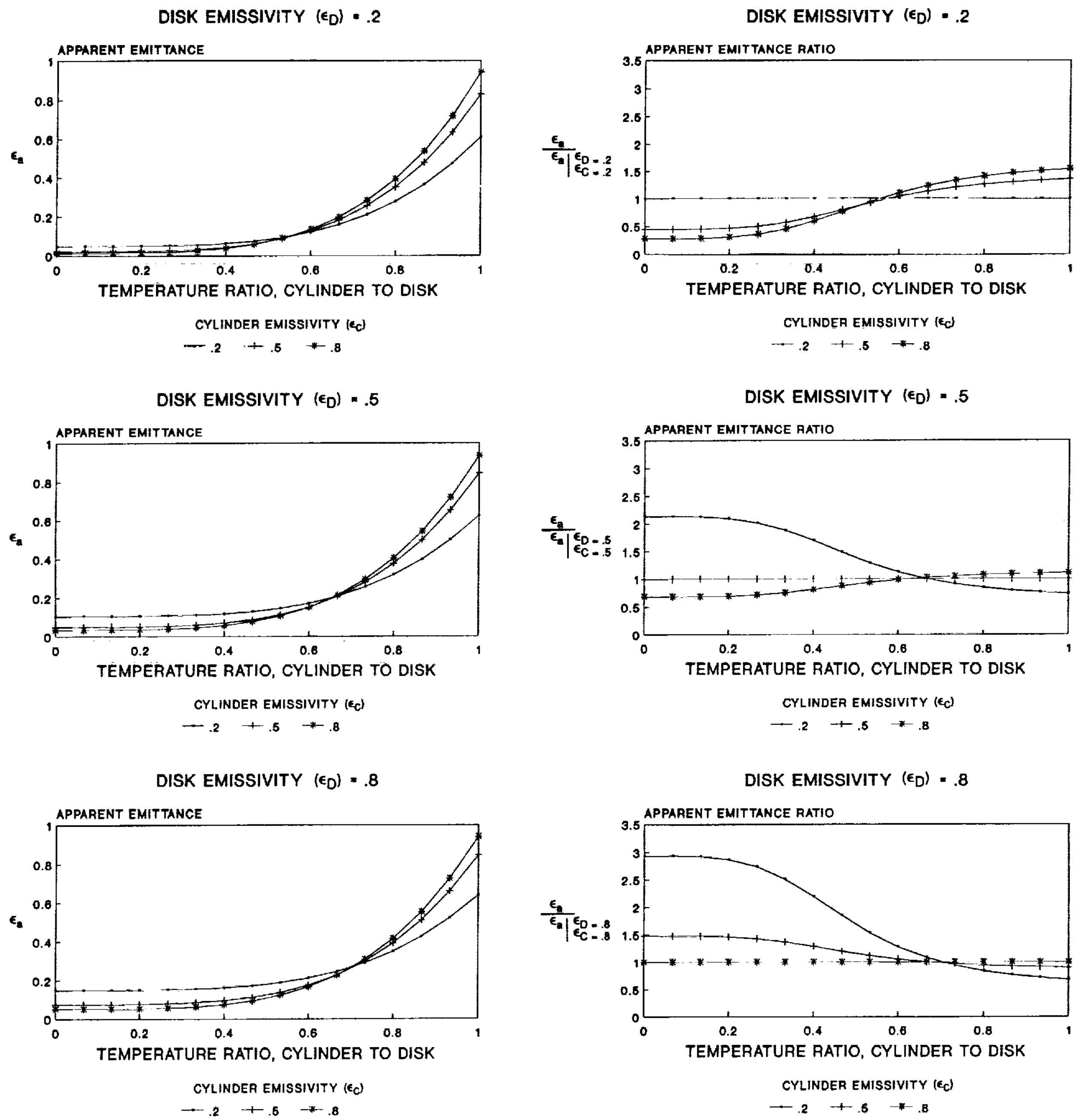

Figure 5.— Apparent emissivity results, L/R = 4.0.

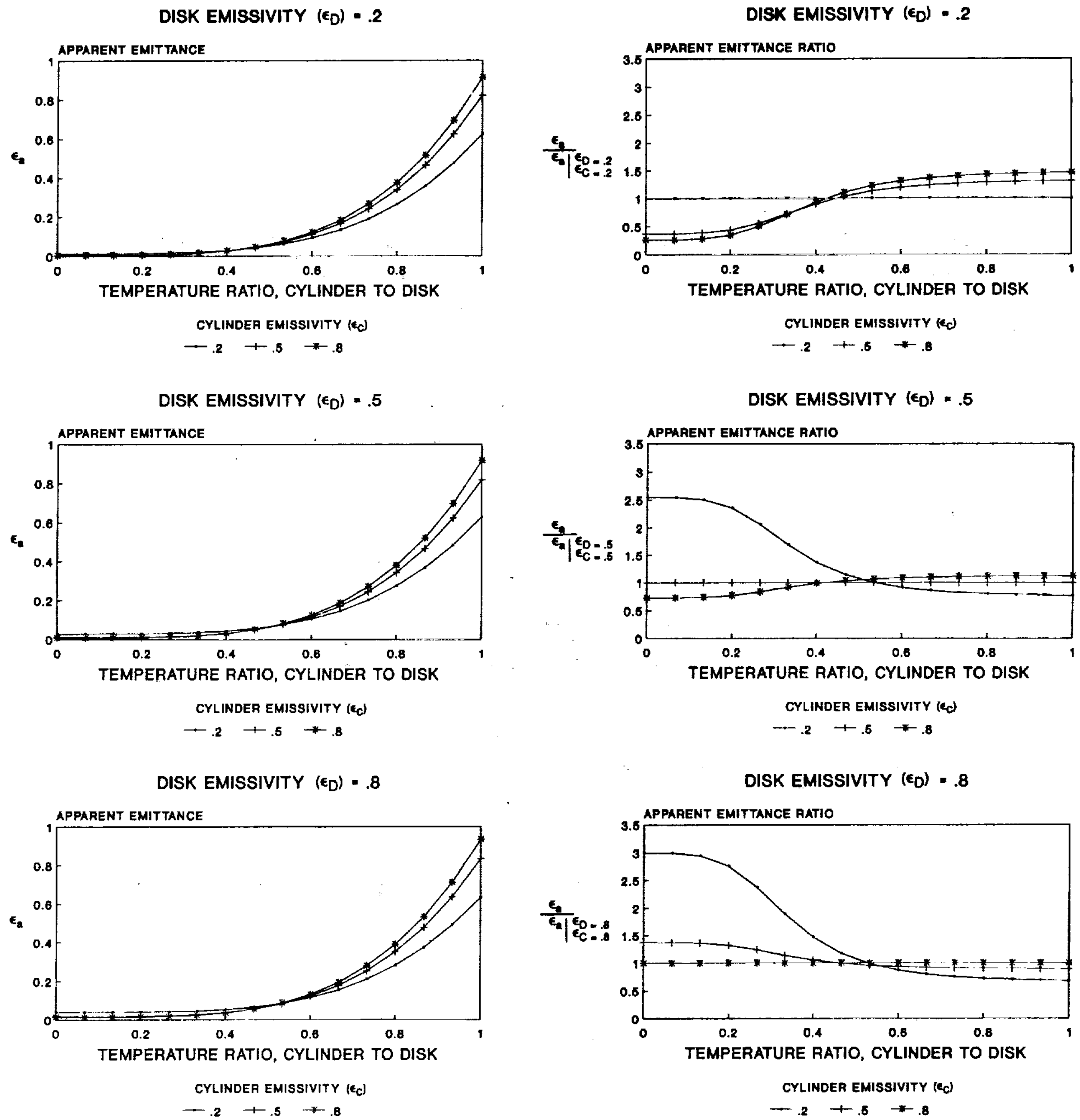

Figure 6.—Apparent emissivity results, L/R = 8.0.

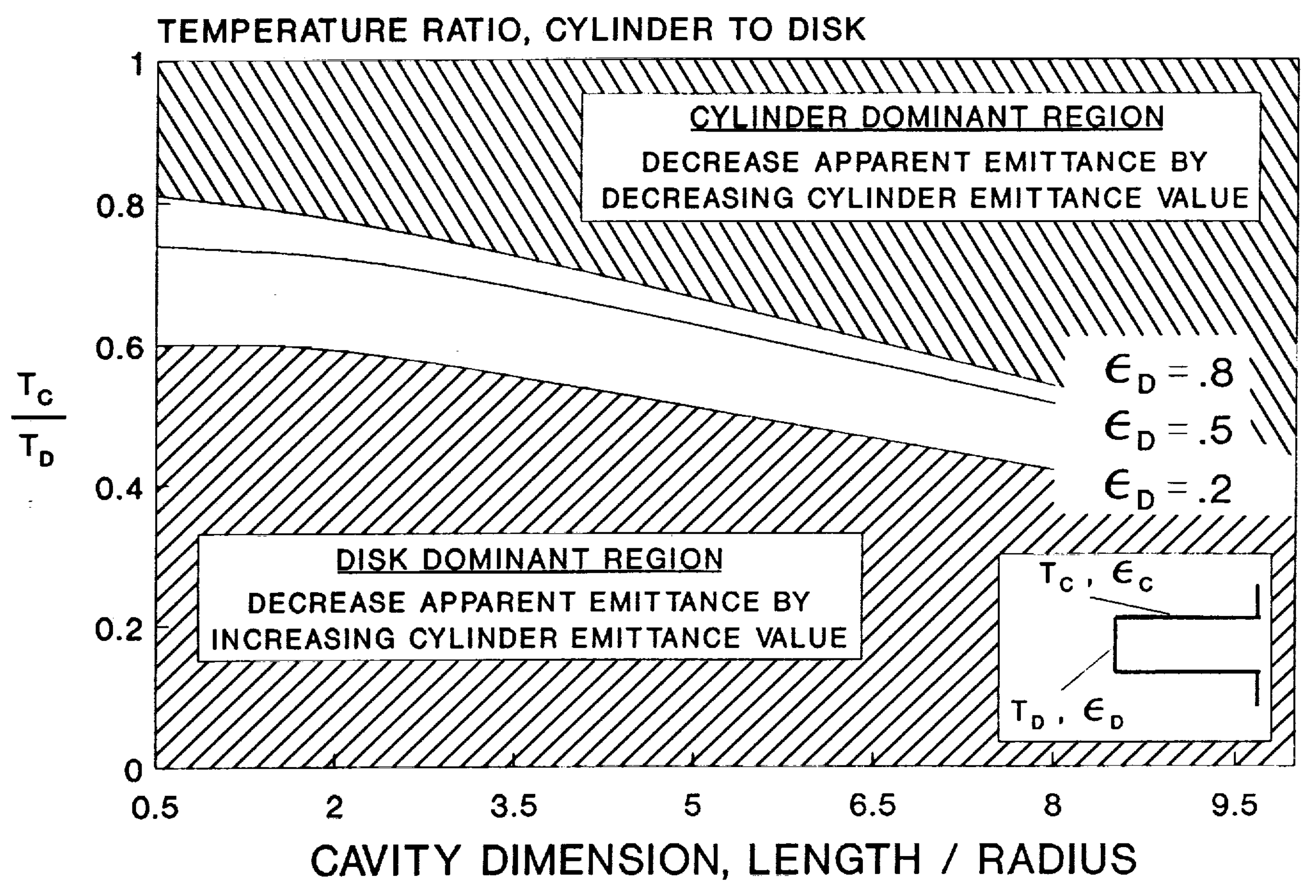

Figure 7.—Effects of optical coatings on cylindrical cavity radiation.

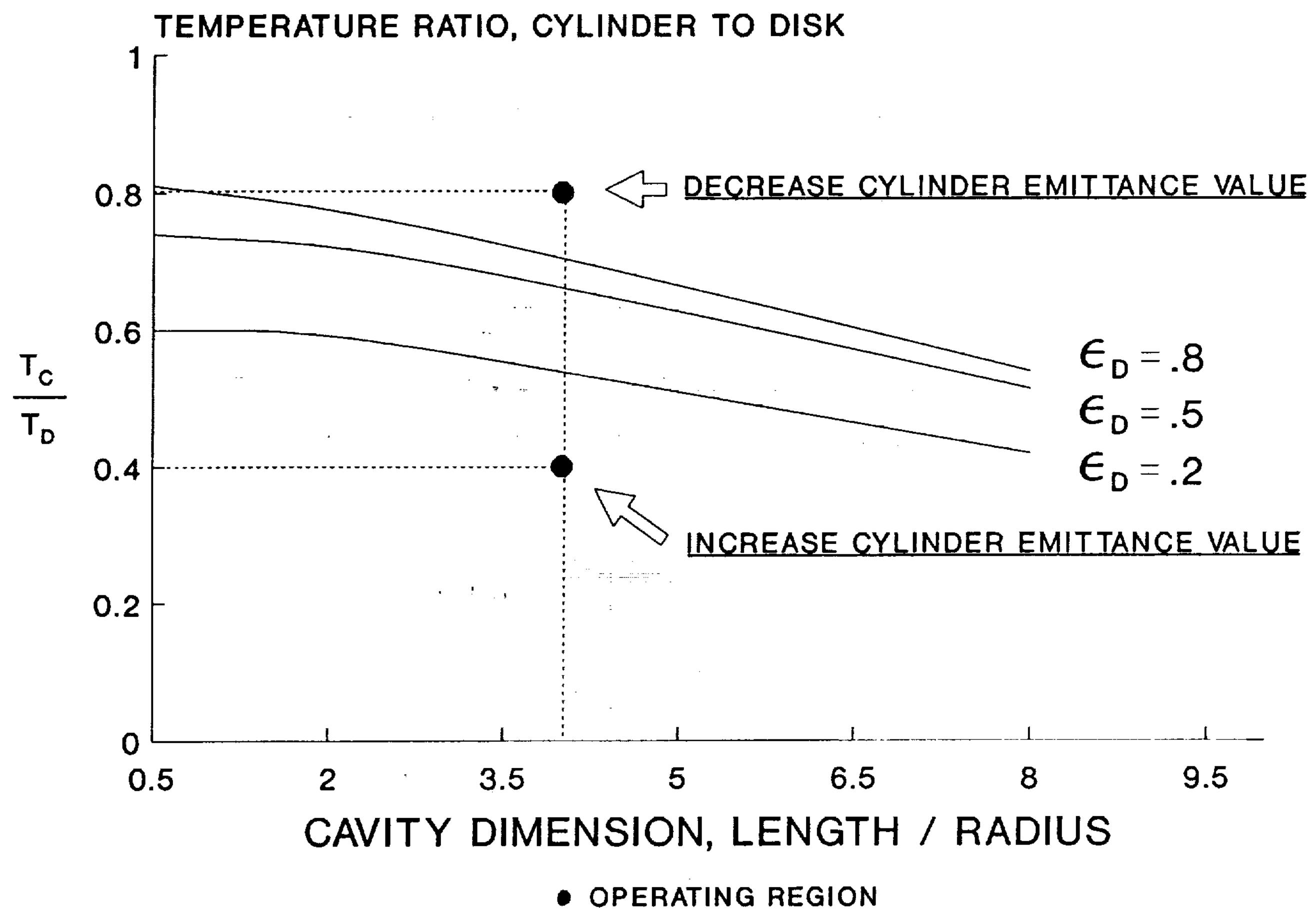

Figure 8.—Sample case, reducing cavity emitted radiation.

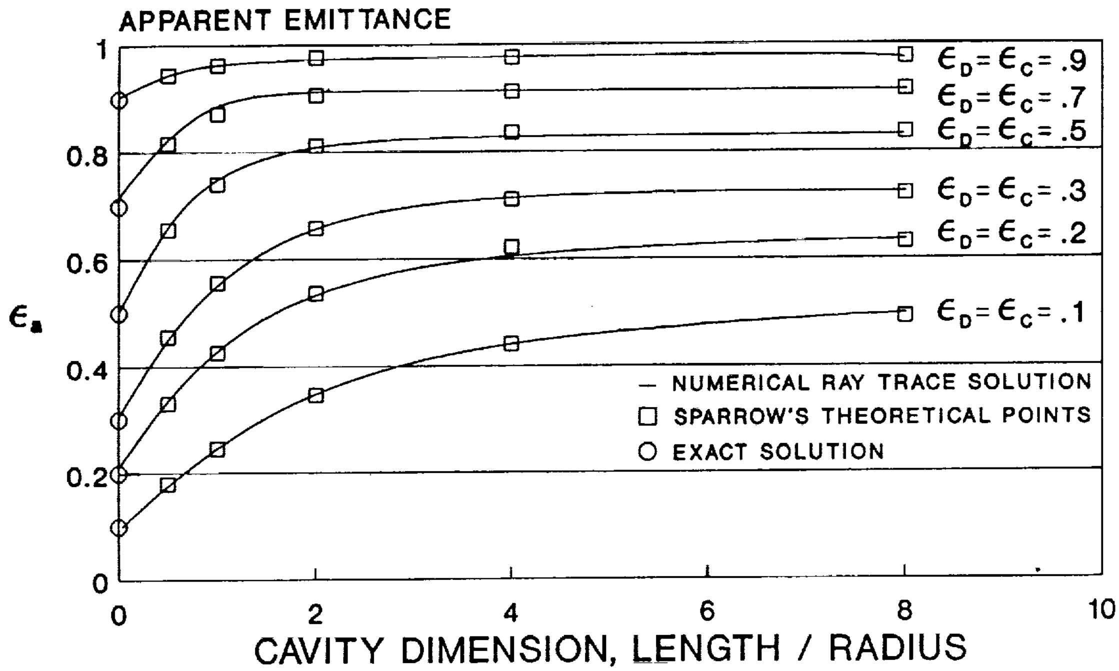

Figure A1.—Apparent emissivity results for diffusely reflecting isothermal cylindrical cavities.

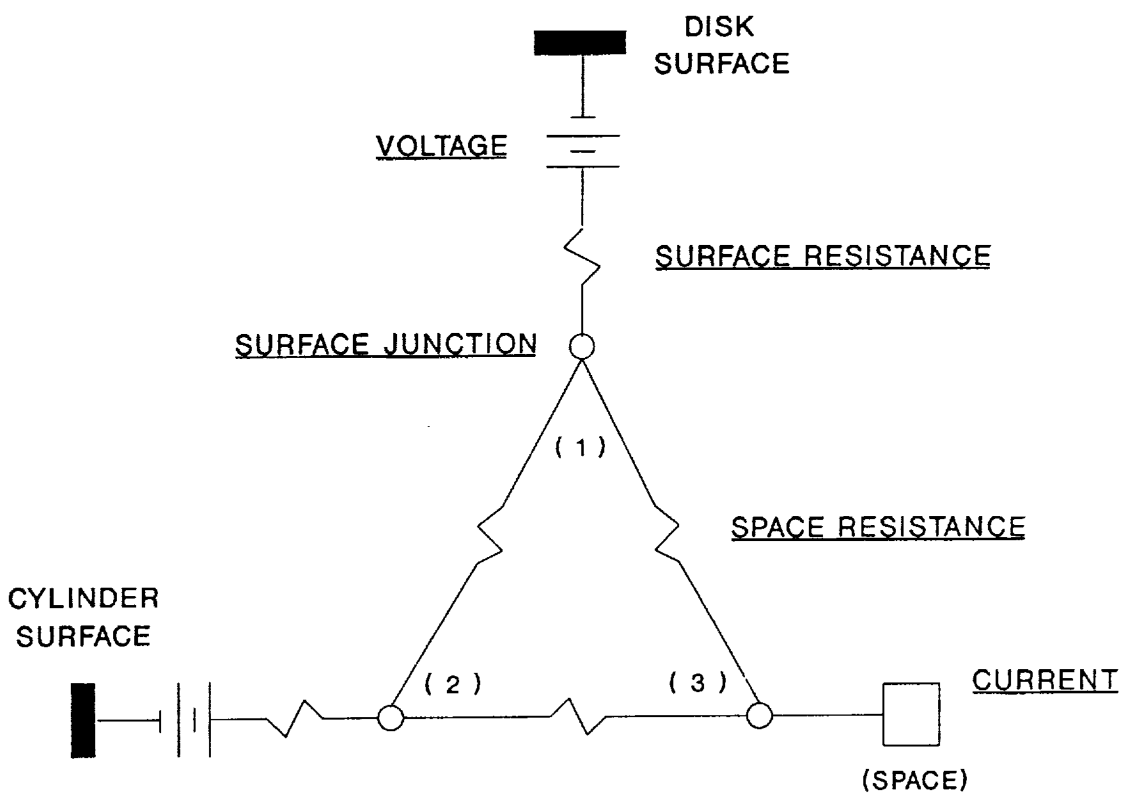

Figure A2.—Cavity resistance network method.

APPENDIX A - NUMERICAL RAY TRACING TECHNIQUE VALIDATION

The radiation emitted from a simple or complicated cavity design may be composed of direct surface emission and multireflecting energy. The multireflecting energy can lead to a nonuniform distribution of radiant energy within the cavity walls. The process of analyzing simple or complex cavity geometries can be simplified by applying a numerical ray tracing approach to simulate the nonuniform radiation propagation. The numerical ray tracing technique enables one to evaluate the radiation heat transfer from a multisectioned cavity to its various cavity sections and the radiation projected out the cavity. To validate the numerical ray tracing approach for use in studying complex cavities of various geometries, a study was preformed that compared the numerical ray tracing results with a known theoretical solution, limiting solutions, and an electrical resistance network method.

A schematic diagram of the analyzed cylindrical cavity is shown in figure 1, where the cylinder displays a uniform cylinder wall temperature case. The apparent emissivity results for the isothermal cavities ($T_D = T_C$) are plotted in figure A1 for various L/R values and a range of surface emissivity values for diffusely reflecting cavity components where $\varepsilon_D = \varepsilon_C$. As a validation check, figure A1 displays the apparent emissivity distribution for an isothermal numerical ray tracing analysis against Sparrow's (1963,1966) theoretical approach and the limiting solution derived in Baumeister (1990), were:

$$\varepsilon_a \Big|_{L/R \to 0} = \varepsilon_D \tag{A1}$$

Sparrow has presented theoretical solutions for various isothermal gray-diffuse cylindrical geometries with uniform emissivity throughout the cavity. The numerical ray tracing results compared exactly with Sparrow's points and agree with the limiting solution for this isothermal case.

In addition, the resistance network method was also applied in analyzing emitted energy from isothermal cylindrical cavity configurations as a possible validation check and to evaluate limiting solution criteria for use as a possible simplified solution technique. The standard resistance network method (Holman, 1986), models only uniform radiosity and irradiation, as shown in figure A2. Table A1 displays apparent emissivity results from the numerical ray tracing technique and the resistance network method for several cavity dimensions. For relatively small cavities (L/R < 2), the resistance network analysis, for all practical purposes, resulted in exact agreement with the ray tracing technique applied with equation (4) and with Sparrow's solution. In these shallow cavities the resistance network method accurately predicts the energy out the cavity for the entire range of surface emissivity values. For cavities with L/R dimensions larger than 2, the difference between the two analysis methods becomes evident. The L/R = 4 results display a widening discrepancy between results at lower cavity emissivity values. This results from a resistance network method assumption requiring equal radiant energy distributions on individual surface sections (radiosity and irradiation). To satisfy these requirements, the cavity can be sectioned so the energy distribution is approximately uniform over each surface. Once proper cavity sectioning is achieved, the results, for practical purposes, agree exactly with the numerical ray tracing technique and Sparrow's theoretical results.

Therefore, for cavities with L/R dimensions greater than 2, the resistance network method requires sectioning the cylindrical walls into smaller individual surfaces. The problem associated with the use of the resistance network method is one of properly sectioning the cavity to achieve uniform energy distribution within each surface, which also may result in complicated view factor relationships and a large set of simultaneous equations to solve.

Comparing results derived from the various techniques applied to multi-sectioned cylindrical cavities reveals that using equation (3) with the numerical ray tracing technique can properly evaluate the total radiant energy emitted from the cavities, the radiant energy emitted from individual cavity sections, and the radiation exchanged from individual sections within the cavity. The cavities need not be sectioned into individual surfaces with uniform incident radiant energy distributions, but rather surfaces only to define the cavity geometry. Another advantage of the numerical ray tracing technique is the ability to modify the basic ray tracing procedure (for radiation propagation) to simulate complicated radiation functions such-as bidirectional reflectance or absorbing media. With this validation of the ray tracing technique, it can now be applied with greater confidence in analyzing more complicated cavity designs.

TABLE A1. - APPARENT EMISSIVITY RESULTS RAY TRACING AND RESISTANCE NETWORK METHOD

[Isothermal cylindrical cavity.]

Cavity emissivity	Apparent emissivity results							
	L/R = 0.5		L/R = 1.0		L/R = 2.0		L/R = 4.0	
	Ray tracing[a]	R.N.M.[b]	Ray tracing	R.N.M.	Ray tracing	R.N.M.	Ray tracing	R.N.M.
0.1	0.180	0.181	0.248	0.250	0.347	0.357	0.448	0.499
0.2	.329	.332	.425	.428	.535	.555	.607	.691
0.3	.455	.459	.557	.562	.656	.682	.711	.791
0.5	.657	.662	.743	.749	.811	.833	.830	.899
0.7	.814	.819	.876	.874	.909	.921	.915	.952
0.9	.946	.945	.964	.964	.977	.978	.980	.972

[a]Numerical ray tracing techinique.
[b]Resistance network method.

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16. Abstract
A numerical ray tracing technique was applied to simulate radiation propagating from various non-isothermal cylindrical cavities to determine the effect of optical coatings (surface emissivity). In general, the analysis showed that the optical coating and temperature within a cavity have a significant effect on emitted radiation based on cavity dimension. Temperature thresholds were found to exist where the same optical coating may either reduce or increase cavity performance (apparent emissivity). Parametric values of apparent emissivity results are presented over a wide range of variables to correlate cylindrical cavity radiation for non-uniform cavity emissivity values. A universal curve has been developed to aid in selecting wall emissivity values for design considerations.

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